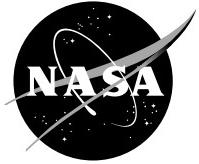


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# Advanced Stirling Technology Development at NASA Glenn Research Center

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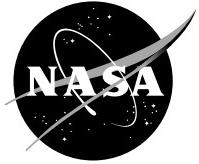
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# Advanced Stirling Technology Development at NASA Glenn Research Center

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## Summary

The NASA Glenn Research Center has been developing advanced energy-conversion technologies for use with both radioisotope power systems and fission surface power systems for many decades. Under NASA's Science Mission Directorate, Planetary Science Theme, Technology Program, Glenn is developing the next generation of advanced Stirling convertors (ASCs) for use in the Department of Energy/Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG). The next-generation power-conversion technologies require high efficiency and high specific power (watts electric per kilogram) to meet future mission requirements to use less of the Department of Energy's plutonium-fueled general-purpose heat source modules and reduce system mass. Important goals include long-life (>14-yr) reliability and scalability so that these systems can be considered for a variety of future applications and missions including outer-planet missions and continual operation on the surface of Mars. This paper provides an update of the history and status of the ASC being developed for Glenn by Sunpower Inc. of Athens, Ohio.

## Background

For many decades, the NASA Glenn Research Center has been developing advanced energy-conversion technologies for radioisotope power systems and fission surface power systems (refs. 1 to 3). Glenn is now developing advanced Stirling convertors (ASCs) for the Department of Energy/Lockheed Martin (DOE/LM) Advanced Stirling Radioisotope Generator (ASRG) (refs. 4 and 5).

In 2002, NASA released NASA Research Announcement (NRA) 02-OSS-01 entitled "Radioisotope Power Conversion Technology" (RPCT), requesting proposals for the development of next-generation power-conversion technology (ref. 6). The objective of the RPCT Project is to advance the development of power-conversion technologies to provide higher efficiencies and specific power than the state-of-the-practice general-purpose heat source (GPHS) Radioisotope Thermoelectric Generator (RTG). Other goals include safety, long life (>14 yr with well-understood degradation), reliability, scalability, multimission capability (in Mars' atmosphere or in the vacuum of space), resistance to radiation (from the GPHS or potential mission environments), and minimal interference with the spacecraft payload. The focus of the NRA contracts is

to develop the power-conversion technology: converting heat to electric power.

The RPCT Project was initiated in the summer/fall of 2003 when 10 contracts were awarded by Glenn. Five awards were for "development" contracts using more mature technology (between technology readiness levels (TRLs) 3 and 5) and five awards were "research" contracts using less mature technology (TRLs 1 to 3). The development contracts selected included a broad range of conversion technologies including the free-piston Stirling convertor (ref. 7), the turbo-Brayton converter (ref. 8), thermoelectric generators (ref. 9), and thermophotovoltaic generators (refs. 10 and 11). The NRA contracts were originally divided into three 1-yr phases, with options to continue into the next phase based on Government review of status. Annual reviews were conducted for the 10 NRA RPCT contracts at the end of both Phase I and Phase II (ref. 5). Currently two Phase III development contracts continue—for the advanced Stirling convertor (ASC) free-piston Stirling convertor with Sunpower Inc. (Athens, OH) and the thermophotovoltaic convertor with Creare (Hanover, NH)—and one research contract continues—for the microfabricated Stirling regenerator with Cleveland State University (Cleveland, OH). The fourth contract that continued into Phase III was with the Massachusetts Institute of Technology (Cambridge, MA) for nano-silicon-germanium thermoelectrics research that has been concluded. This paper provides the status of the development of the ASC by Sunpower Inc.

## Advanced Stirling Convertor Development

### Phase I

Sunpower Inc. is leading a team consisting of United Technologies Companies—Rocketdyne (UTC-R, previously known as Pratt & Whitney Rocketdyne), the University of Minnesota, and several consultants to demonstrate the technology of an ASC. The ASC consists of the free-piston Stirling engine integrated with a linear alternator to produce electricity. The key technologies in the ASC that enable high efficiency and low mass are the hydrostatic gas bearings, a moving-magnet linear alternator, high-frequency operation (>100 Hz), high-temperature heater head materials and fabrication processes, and high-temperature, high-porosity regenerators. The charge pressure of the ASC is 3.5 MPa, and the frequency is about 105 Hz. The original goals of the ASC



Figure 1.—Sunpower Frequency Test Bed Stirling convertor.

were to achieve an efficiency of greater than 30 percent (alternating current (ac) power out/heat in), with a design output power of greater than 80-We ac, making feasible a projected radioisotope power system (RPS) specific power of about 8 We/kg (ref. 12). As identified in the remainder of this paper, the ASC performance goals have now been met.

The ASC being developed uses technologies similar to those of Sunpower's commercial cryocoolers. A Sunpower cryocooler is currently being used on NASA's RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) satellite, which was launched in February 2002.

During Phase I, Sunpower designed and built a Frequency Test Bed (FTB) Stirling convertor to investigate the advanced technologies in their proposal. Use of the FTB would allow evaluation of the advanced concepts and provide guidance on the design for the ASC. The FTB was made operational within the first 5 months of Phase I. The performance surpassed the goals (>30 percent) of the project, demonstrating 36-percent conversion efficiency (ac power out/heat in) at a 650 °C heater head operating temperature and a 30 °C rejection temperature with a power output of 80-We ac. Operation of the FTB (fig. 1) at these temperatures represents a temperature ratio of 3, which is representative of the Sunpower ASC design that would operate at the higher temperatures of 850 °C (heater head) and 90 °C (rejection).

The ASC-1s (fig. 2) were designed during Phase I, and four nonhermetically sealed units were planned for fabrication during Phase II. The ASC is designed to operate at a heater



Figure 2.—Four nonhermetically sealed advanced Stirling convertors (ASC-1s).

head temperature of 850 °C using available materials technology with MarM-247. Prior to the selection of MarM-247, a variety of candidate high-temperature materials were considered by the Sunpower team including materials that were evaluated and recommended by NASA (refs. 13 and 14).

Creep testing of the MarM-247 head material continues with thin test samples that replicate the heater head wall thickness. Over 30 creep tests have been completed to date, characterizing a range of MarM-247 casting variables and specimen thickness. The heater head is designed with a conservative approach including estimates based on these data. Although the use of Inconel 718 has been demonstrated to show sufficient life (17 yr) at 640 °C when used in the ASC, analysis of MarM-247 (0.999 probability of survival) shows that the design life of the heater head operating at 850 °C is in excess of 70 yr. Use of MarM-247 greatly enhances the reliability by providing significant margin in the ASC design.

For the RPS 14-yr life requirement and the high-temperature requirements of the ASC, the creep strength of the thin-walled heater head pressure vessel is paramount. After reviewing the creep data provided by NASA, the ASC team also conducted thin-sample creep testing of MarM-247. Analysis indicated that the projected 1-percent creep over the heater head over 14 years would have no impact on the ASC performance. The ASC project team developed a variety of coupon, joining, and processing tests that were carried out during Phases I and II to develop the proper processing techniques for the heater head.

In addition to the development of the convertor hardware and materials development work, significant effort during Phase I involved reliability studies, component testing, advanced component investigations, and thermodynamic loss investigations.

## Phase II

During Phase II, Sunpower completed the design and fabrication of four nonhermetically sealed ASC-1s that can operate with a heater head temperature of 850 °C. The purpose of the

multiple convertors is to gain initial operating experience with nonhermetically sealed laboratory developmental convertors using the higher temperature materials operating in single- and dual-opposed configurations. Testing and operation of these units would further guide the design of the hermetically sealed ASC-2s to be built in Phase III. Two of the ASC-1s have all-MarM-247 heater heads, and two have an inertia-welded MarM-247 heater head.

Besides the MarM-247 heater head, high-temperature displacers, regenerators, and hot cylinders are required to allow the ASC-1 to operate at the higher operating temperatures. During Phase II, Udimet 720 displacer dome and baffle processing and joining were demonstrated as was the incorporation of the Udimet 720 hot cylinder. On the basis of prior work, Glenn recommended the oxidation-resistant high-temperature regenerator material, and later developed the processing of the regenerator sections and provided them for inclusion in the convertor build.

Testing during Phase II demonstrated the ASC-1 conversion efficiency of 38-percent (ac out/heat in) with 88-We ac power output at 850 °C hot-end and 90 °C cold-end temperatures. It should be noted that the ASC-1 design is capable of higher power output if unconstrained to the thermal input limit of a GPHS. During testing, the ASC-1 demonstrated a maximum power output of 114-We ac.

As part of the reliability assessment, during Phase II the Hot Alternator Test Rig was developed to characterize ASC linear alternator performance at elevated temperatures and then to destructively test the alternator to identify temperature-induced failure mechanisms.

### Phase III

Because of the successful performance demonstrations and continued relevance of the ASC to NASA's future needs, the current Phase III of the project has been modified in three major ways:

(1) Glenn was directed by NASA Headquarters to focus in-house technology efforts to support the development of the ASC.

(2) Four additional accelerated hermetically sealed convertors based on the ASC-1 were ordered. These convertors are intended for 24-hr/7-day extended operation at Glenn to identify and resolve development issues and to provide life and reliability data.

(3) The Glenn/Sunpower contract was modified to include three hermetically sealed ASC-Es to support the development of the Department of Energy/Lockheed Martin (DOE/LM) Advanced Stirling Radioisotope Generator (ASRG).

To allow for this additional work and also to continue developmental efforts prior to commitment to a final design,

the Sunpower contract was extended and fabrication of the ASC-2 was deferred until later in Phase III.

Glenn is supporting the ASC and ASRG development in a number of key areas that focus on the life and reliability of the technology.

- Reliability and quality assurance
- In-house convertor and component testing
- High-temperature materials and structures
- Electromagnetic interference and electromagnetic compatibility
- Computational fluid dynamics modeling of gas bearings
- Organic materials development and characterization
- Magnet aging and characterization
- Support of LM controller development

To provide life and reliability data on and performance evaluation of the ASC, Glenn ordered four additional hermetically sealed convertors based on the ASC-1 intended for extended operation in Glenn's Stirling Research Laboratory: a pair of ASC-0s (Inconel 718, 650 °C operation) and a pair of ASC-1HSs (MarM-247, 850 °C operation). These early hermetically sealed units would be used to identify development issues and to develop processing techniques for the later hermetically sealed convertors. A pair of ASC-0s (fig. 3) was delivered to Glenn in December 2006. Initial testing was completed in air for over 600 hr, and the convertors are currently operating in a thermal-vacuum environment in Glenn's Stirling Research Laboratory. The ASC-0s had accumulated over 2800 hr of operation as of May 2007. The ASC development convertors currently in operation are shown in table I. The ASC-1HS pair is scheduled for delivery to Glenn in summer 2007 and will undergo extended operation in the thermal vacuum facility.

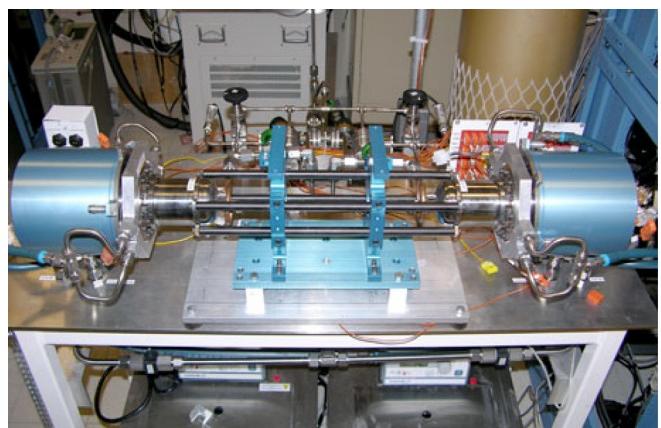


Figure 3.—Advanced Stirling convertors (ASC-0) #1 and #2 in Glenn's Stirling Research Laboratory.

TABLE I.—STIRLING CONVERTORS (ASCs) FOR DEVELOPMENT CURRENTLY IN OPERATION

Model	Units	Head material	Temperature, °C		Power (ac), W	Design features	Comments
			$T_{\text{hot}}$	$T_{\text{cold}}$			
FTB <sup>a</sup>	2	Stainless steel	650	30	85	Nonhermetic	Development units
ASC-0	2	Inconel 718	650	90	70	Hermetic	Initial testing at Glenn (February 2007)
ASC-1a	2	MarM-247	850	90	88	All-MarM-247 heater head	On test at Sunpower
ASC-1b	2	MarM-247 Inconel 718	850	90	88	Inertia welded heater head	Initial testing at Glenn (May 2007)

<sup>a</sup>Frequency Test Bed.

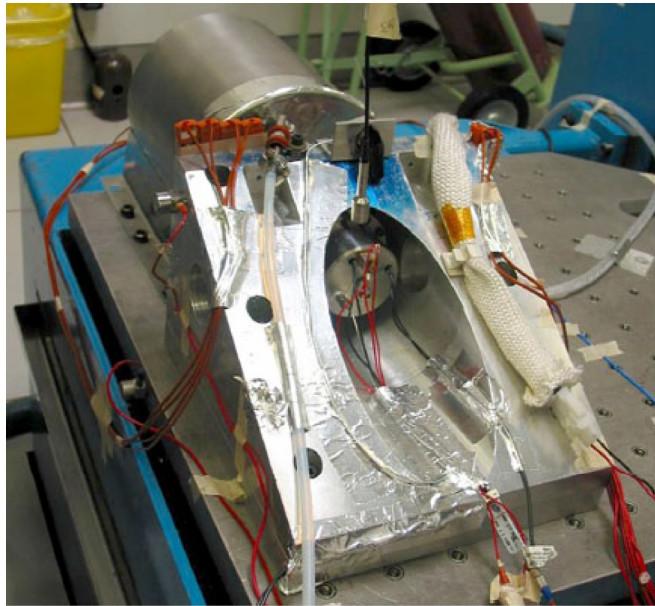


Figure 4.—Sunpower advanced Stirling convertor (ASC-1) #4 installed on vibration table at United Technologies Companies—Rocketdyne.

In April 2007, ASC-1 #4 (shown in fig. 4) completed a series of simulated launch vibration levels at UTC-R. Testing was performed with the ASC producing power in both the axial and lateral directions. Testing was completed at workmanship (6.8 grms random) for 1 min, flight (8.7 grms random) for 1 min, and qualification (12.3 grms random) for 3 min. In addition, ASC-1 #4 was operated at qualification +3 dB (17.5 grms random) for 1 min. The test configuration included demonstration of an internal fast linear displacement transducer, which is a modification in the design for the ASC-E.

After successful launch simulation testing, ASC-1 #4 and a matching convertor, ASC-1 #3, were delivered to Glenn for continuous operation in May 2007. These convertors are now undergoing checkout testing. Testing of two pairs of ASCs, a pair of ASC-0s and a pair of ASC-1s has been initiated at Glenn's Stirling Research Laboratory.

In addition, the braze for the displacer joint was developed, electrical feed-through screening was completed, piston and

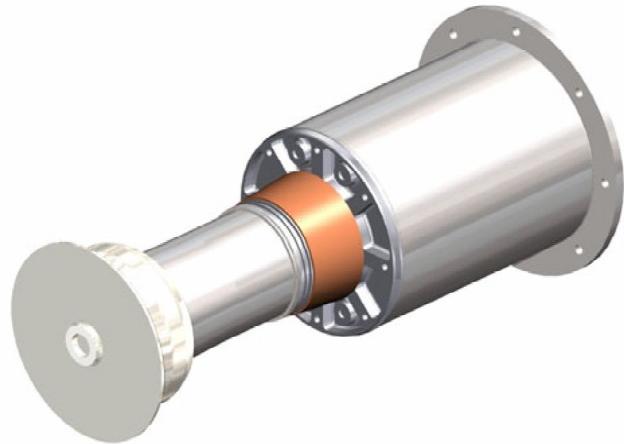


Figure 5.—Sunpower advanced Stirling convertor (ASC-E) to be incorporated into the Department of Energy/Lockheed Martin Advanced Stirling Radioisotope Generator engineering unit.

centerport evaluation and development were completed, and regenerator fabrication and procedures were completed as part of the development project. During Phase II, procedures were initiated to prepare for the manufacturability of the ASC-Es.

ASC-E (shown in fig. 5) is the designation for the converters that are intended for incorporation into the DOE/LM ASRG engineering unit (EU). Although other ASC machines are intended as laboratory units, by design the ASC-Es are intended for integration onto an EU of an RPS, thus requiring different interfaces and generator system input.

At the outset of the ASC-E design, tradeoff studies were performed by Sunpower, Glenn, and LM to determine

- Heat collector interface with the GPHS
- Cold-side adapter flange interface with the generator housing/radiator
- Piston position sensor
- Feedthroughs
- Piston centering
- Controller approach
- Launch simulation evaluation

Glenn and Sunpower conducted a design review of the ASC-E design in November 2006. The ASC-E design has

TABLE II.—PHASE III ADVANCED STIRLING CONVERTORS (ASCS) FOR DEPARTMENT OF ENERGY/LOCKHEED MARTIN ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG) ENGINEERING UNIT (EU) AND DEVELOPMENT

Model	Units	Head material	Temperature, °C		Power (ac), W	Design	Delivery dates
			$T_{\text{hot}}$	$T_{\text{cold}}$			
ASC-1HS	2	MarM-247/Inconel 718	850	90	88	Hermetic	Summer 2007
ASC-E	3	Inconel 718	650	60	75	Hermetic	October 2007 for ASRG EU
ASC-2	4	MarM-247/Inconel 718	850	90	88	Hermetic	August 2008

TABLE III.—COMPARISON OF 650 AND 850 °C ADVANCED STIRLING RADIOISOTOPE GENERATORS (ASRGs)

Parameter	650 °C ASRG	850 °C ASRG
Technology	Stirling convertor with 650 °C heater head	Stirling convertor with 850 °C heater head
Power per ASRG at BOL, <sup>a</sup> We	143	~160
Power degradation, <sup>b</sup> percent/yr	0.8	0.8
Mass per ASRG, kg	~23	~19
Dimensions		
Length, mm	725	TBD <sup>c</sup>
Width, mm	293	TBD <sup>c</sup>
Height, mm	410	TBD <sup>c</sup>
Number of GPHS <sup>d</sup> modules	2	2
Thermal power at BOL, <sup>a</sup> Wt	500	500
ASRG specific power	7.0	~8.4
Controller	Single fault tolerant	Single fault tolerant
Operating environment	Vacuum and Mars atmosphere	Vacuum and Mars atmosphere
Life requirement	14-yr mission + 3-yr storage	14-yr mission + 3-yr storage

<sup>a</sup>Beginning of life.

<sup>b</sup>Power decays with fuel decay.

<sup>c</sup>To be determined.

<sup>d</sup>General-purpose heat source.

been frozen and is under configuration control at Glenn. Three ASC-Es are being provided as Government-furnished property to the DOE ASRG project and will be delivered in October 2007. The Phase III ASC hardware being fabricated is shown in table II.

## Key Accomplishments

Key accomplishments and benefits of the Sunpower ASC development project follow:

- The Phase I FTB demonstration surpassed the performance goal (30 percent), demonstrating 36-percent efficiency at 650 °C heater head and 30 °C rejection temperatures.
- The Phase II ASC-1 is completed and operational. It surpassed the performance goal, demonstrating 38-percent efficiency with 88-W ac power at 850 °C heater head and 90 °C rejection temperatures.
- NASA directed the use of the Sunpower ASC within the 110-W Stirling Radioisotope Generator (SRG110) design in March 2006. This resulted in significant improvement (2 times) of generator specific power: from the SRG110 at ~3.5 We/kg to the ASRG at ~7.0 We/kg.
- The Sunpower ASC-E design review was completed in November 2006.

- The DOE/LM ASRG EU final design review was completed in February 2007.
- Initial operation and testing of the ASCs at Glenn was initiated in February 2007.
- ASC-1 #4 successfully passed a launch vibration test at UTC-R in April 2007.

## Advanced Stirling Radioisotope Generator

The Sunpower ASC has been substituted into the DOE/LM SRG110 design, resulting in the ASRG (ref. 12). The new generator design consists of a beryllium housing, two advanced Stirling convertors, an electronic controller with single-fault-tolerance design, and one GPHS at each end held by a heat source support with bulk thermal insulation. Thermal-to-electric power conversion is provided by two free-piston Stirling engines, each integrated with a linear alternator (Stirling convertor) designed in a hermetically sealed pressure vessel. Each Stirling convertor produces ac electrical power that is converted to direct-current (dc) power by the controller.

Currently there are two ASRG design configurations, the ASRG EU, which is currently being developed and uses the ASC with the 650 °C heater head temperature, and a higher specific power ASRG, which uses the ASC with the 850 °C heater head temperature (see table III). The 650 °C ASRG

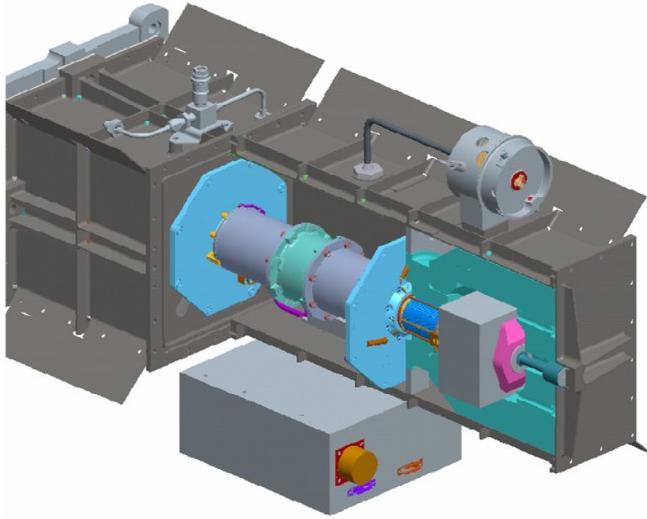


Figure 6.—Department of Energy/Lockheed Martin Advanced Stirling Radioisotope Generator engineering unit.

design will be able to deliver 143-We dc with a specific power of 7 We/kg at beginning of life (28-percent system conversion efficiency). The 650 °C ASRG EU will use the ASC-Es currently being developed by Sunpower. LM completed a final design review of the ASRG EU using the 650 °C Stirling convertor in February 2007. The ASRG design (shown in fig. 6) is reviewed in detail by Richardson and Chan (ref. 15). An ASRG using the 850 °C ASC would enable an RPS with greater than 8-W/kg specific power and greater heater head design margin (ref. 12).

## Conclusions

In summary, the technology development for the Sunpower advanced Stirling convertor (ASC) has made significant progress: Phase I demonstrated the advanced technologies in the Frequency Test Bed, exceeding their original goals; Phase II demonstrated high efficiency (38 percent) in a high-temperature, low-mass ASC, resulting in a projected convertor specific power of ~90 We/kg. Consequently, in March 2006 the ASC was selected to be used with the Department of Energy/Lockheed Martin (DOE/LM) Advanced Stirling Radioisotope Generator (ASRG) engineering unit (EU). ASC-Es are being manufactured for the DOE/LM ASRG EU for delivery in October 2007. The system specific power (>7 We/kg) of the resulting ASRG EU will be a significant improvement over the state-of-practice Radioisotope Thermoelectric Generator. Phase III continues the development of the ASC using existing high-temperature materials (MarM-247 at 850 °C) and has made substantial progress, providing significantly improved margins for use with the future ASRG.

Glenn Research Center  
National Aeronautics and Space Administration  
Cleveland, Ohio, September 17, 2007

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<b>14. ABSTRACT</b> The NASA Glenn Research Center has been developing advanced energy-conversion technologies for use with both radioisotope power systems and fission surface power systems for many decades. Under NASA's Science Mission Directorate, Planetary Science Theme, Technology Program, Glenn is developing the next generation of advanced Stirling convertors (ASCs) for use in the Department of Energy/Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG). The next-generation power-conversion technologies require high efficiency and high specific power (watts electric per kilogram) to meet future mission requirements to use less of the Department of Energy's plutonium-fueled general-purpose heat source modules and reduce system mass. Important goals include long-life (>14-yr) reliability and scalability so that these systems can be considered for a variety of future applications and missions including outer-planet missions and continual operation on the surface of Mars. This paper provides an update of the history and status of the ASC being developed for Glenn by Sunpower Inc. of Athens, Ohio.					
<b>15. SUBJECT TERMS</b> Radioisotope power systems; Fission power systems; Stirling conversion systems; Stirling convertors					
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